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Investigation of Alfvén waves in a helicon plasma

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Helicon wave sustained discharges provide high density plasmas needed to investigate Alfvén waves under laboratory conditions. In the present paper kinetic Alfvén waves were successfully launched in a helium plasma. A good agreement is found between the measured and the theoretically predicted dispersion behaviour. The damping can be associated both to collisional and Landau damping.

1. Introduction

Alfvén waves are known to play a major role in the dynamics of magnetized plasmas. Motivated by their importance in plasma heating, transport of energy, and information about perturbations in the magnetic field topologies, Alfvén waves have been subject of intense research in laboratory, space and astrophysical plasmas [1]. Two different principal modes of Alfvén waves can be observed, both propagating below the ion cyclotron frequency. Firstly, magneto-acoustic waves propagate perpendicular to the ambient magnetic field B_0. Secondly, shear Alfvén waves propagate along the magnetic field lines. The kinetic and inertial regime of Alfvén wave propagation can be distinguished, depending on the plasma-beta value, where beta is given by the ratio between kinetic and magnetic pressure. For $\beta > m_e/m_i$, which is for $T_e \gg T_i$ equivalent to $v_A < v_{th,e}$, Alfvén waves are kinetic. Here $v_A = B/(\mu_0 m_i n_i)^{1/2}$ is the Alfvén velocity and $v_{th,e} = (kT_e/m_e)^{1/2}$ is the electron thermal velocity. For $\beta < m_e/m_i$ Alfvén waves are inertial.

For laboratory experiments on Alfvén waves, a challenge is always their extremely long wavelengths. This requires first of all a large plasma device. Because of $v_A \propto n_i^{-1/2}$, a high plasma density leads to reasonably short wavelengths being smaller than the device dimension. At such high densities $\beta \simeq 0.5 \ldots 8.5\, m_e/m_i$ and one is mostly in the kinetic regime. The kinetic treatment of ion dynamics in magnetized plasmas yields an expression for the dispersion of shear Alfvén waves as [2]

$$\frac{\omega^2}{k_\parallel^2} = v_A^2 \left(1 + k_\perp \rho_s^2\right) . \qquad (1)$$

Here $\rho_s = c_s/\omega_{ci}$ is the so-called ion sound gyroradius and the wave number is $k = k_\perp + k_\parallel$. Collisionless damping is important in the kinetic regime and the damping rate for Alfvén waves reads

$$\gamma = \frac{1}{2}\left(\frac{\pi}{2}\right)^{1/2} \left(\frac{m_e}{m_i}\right)^{1/2} \frac{k_\perp^2 v_A^2}{\omega_{ci}^2} |k_\parallel|\, v_s , \qquad (2)$$

with the ion cyclotron frequency $\omega_{ci} = eB/m_i$ and the ion sound speed $v_s = (kT_e/m_i)^{1/2}$.

2. Experimental Setup

Experiments were conducted in the VINETA device [3]. Figure 1 shows a schematic diagram of the experimental device. The vacuum chamber consists of four identical modules, 0.4 m in diameter and 1.2 m in length. The four chambers are immersed in a set of 36 magnetic field coils ($B_0 \leq 100\,\mathrm{mT}$). The plasma source is placed at the one end of the device. A right hand half-turn helical antenna is driven with rf 5 – 30 MHz and electric power of up to 2.5 kW in cw-mode and 6 kW in pulsed mode. Three different discharge modes, capacitive, inductive, and helicon mode can be established. Plasma-densities are found to be in the range of $10^{16} - 10^{19}\,\mathrm{m}^{-3}$. The electron temperature is in the range $1 - 5\,\mathrm{eV}$.

Alfvén waves are launched using a single-loop antenna, which surface normal is oriented perpendicular to the background magnetic field. The relative induced magnetic field perturbation $\delta B/B_0$ is in the range of a few percent. Alfvén-waves are detected with $\dot{B}$-probes by measuring the induced voltage proportional to the magnetic field fluctuations [4]. A computer controlled high-resolution two-dimensional (radial-axial) probe positioning system is used for measurements of propagating wave fronts. Helium is used as filling gas. The neutral gas pressure is in the range of $0.1 - 2\,\mathrm{Pa}$. At maximum magnetic field $B_0 = 100\,\mathrm{mT}$ the ion gyro-frequency is $f_{ci} = 382\,\mathrm{kHz}$ around which the $\dot{B}$-probe is already sufficiently sensitive (note that the induction voltage of the probe scales as $U_{ind} \propto \omega$).

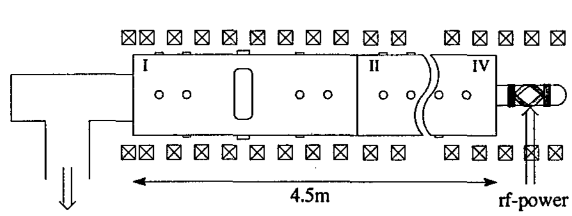

Figure 1: Schematic diagram of the VINETA device. The device consists of four identical modules. Only one complete module is shown in the schematic (module I). On the l.h.s. it is indicated the vacuum pump. On the r.h.s. the helicon source is located.

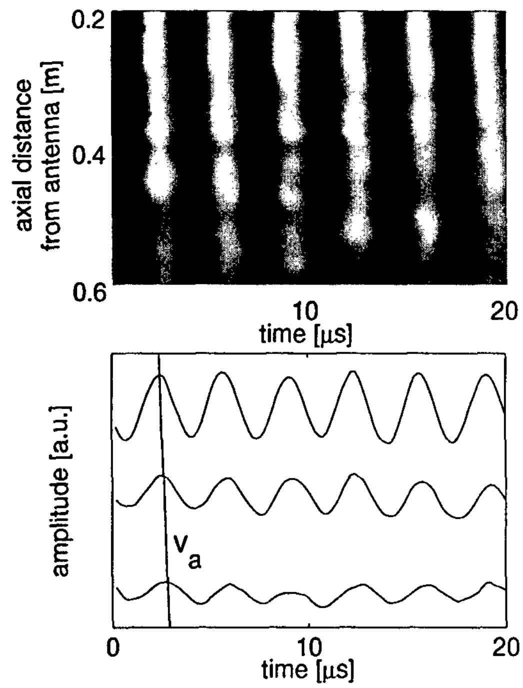

Figure 2: Top: Spatio-temporal measurements of propagating magnetic field fluctuations measured with $\dot{B}$-probes. Bottom: Selected timeseries at axial distances 0.2 m, 0.4 m and 0.6 m relative to the exciter antenna.

In a helium plasma we achieved sufficiently high densities to ensure $\beta \sim m_e/m_i$.

3. Results and Discussion

Experimental data from $\dot{B}$-probe measurements at exciter frequency 300 kHz are shown in Figure 2 (top diagram). The VINETA device is operated in the helicon mode at high rf power and $B_0 = 0.1\,\mathrm{T}$. The amplitude of magnetic fluctuations in axial direction is plotted gray-scale-coded position vs. time. The diagram shows a regular pattern of propagating signals. The bottom diagram in Figure 2 shows three timeseries taken at 0.2 m, 0.4 m and 0.6 m axial distance to the exciter-loop. A sinusoidal propagating wave-type signal is clearly observed. Two different informations can be derived from the diagram: The phase velocity $v_{ph} = 1.2 \cdot 10^6\,\mathrm{m/s}$ of and the damping length $\delta = 0.5\,\mathrm{m}$.
The excitation frequency is varied in the range 160 – 330 kHz and a dispersion diagram is obtained as shown in Figure 3. The errorbars are given by uncertainties in the $\dot{B}$-probe phase detection. The calculated dispersion relation of a kinetic shear Alfvén wave, equation (1), is plotted as solid line in the same diagram. The parameters used are $n_i = 3 \cdot 10^{17}\,\mathrm{m}^{-3}$, $B_0 = 0.1\,\mathrm{T}$ and $k_\perp \approx 0$ is assumed. There is very good agreement between theory and observation.

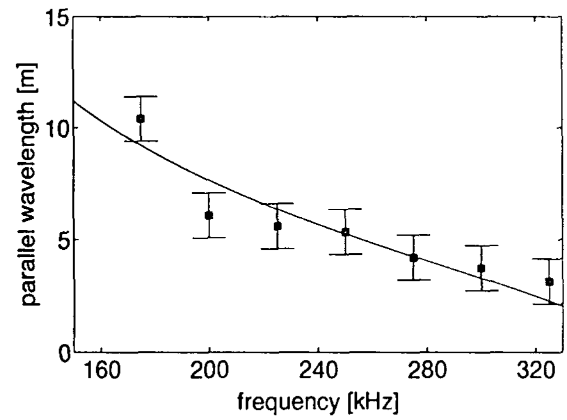

Figure 3: Dispersion diagram of the observed Alfvén waves. The dispersion relation (1) of kinetic shear Alfvén waves is indicated by a solid line.

4. Summary and Conclusion

Kinetic Alfvén waves have been successfully launched in a high-density helium helicon plasma. The dispersion relation of kinetic Alfvén waves could be fully confirmed. The present observations support results recently obtained in a different machine [5]. We note that our measurements are based on the evaluation of the full (averaged) magnetic wave field and not only on a two-point measurement. The relatively strong damping can be assigned to two different mechanisms: Collisional damping is clearly of significance ($\nu_e \approx 800\,\mathrm{kHz}$). At $\beta \sim 1$ ion Landau damping is known to be strong, too [2]. Work is in progress to make a quantitative analysis of propagation and damping of kinetic Alfvén waves in a helicon plasma.

Acknowledgement

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